**The Arch Never Sleeps**
*Lines of Thrust*

**Narrator:**
At Chartres the remains of an earlier cathedral at the base of the West Wall show just how cautious the pre-Gothic architects were. They felt that the forces had to stay within the stonework or it would fall over, so they built massive walls with only small arched windows and added heavy buttresses, or supports, right up against those walls. The use of a physical model can show you how little of the stone is needed for an arch to be stable.

**Francis Evans:**
The idea comes from an engineer called Barlow in the 1840's. It's a proper arch with flat-faced voussoirs, but you see we've put these slats of wood in between them so that the gaps stay parallel. Now let's take out…

**Narrator:**
Between each block there are equal and opposite forces and these forces must pass through the wooden slats - they're the only point of contact - although you can't specify the exact magnitude or direction of these forces.

**Francis Evans:**
… but you can see what's happening. The arch is still perfectly stable. These two faces are staying parallel. That's the face of the abutment and the face of the voussoirs, and they're being held apart just by that very thin slip of wood and so, in fact, the thrust has to be there. And lastly we come here, that's loose, that's loose, and we're down to one slip of wood, so that's all the blocks in the arch have been separated by just one slip of wood in each, and that's certainly where the thrust is running.

**Narrator:**
This arrangement of slats represents one line of thrust but you can have slats in different positions, showing a different line of thrust. In fact, many lines of thrust are possible within an arch and it only takes one line to exist for the structure to stand. Changes to a line of thrust can also be shown in this special model with curved edges to the voussoirs.

**Francis Evans:**
So we've got another arch but with this difference you can make it actually wobble just like a jelly.

**Narrator:**
Each voussoir is in a state of equilibrium. The compression forces can only pass through these points of contact, each force being balanced by an equal force in the opposite direction. A line of action of the thrust would pass through the structure like this. Let's concentrate on just one voussoir. At the contact point on its left face the thrust from the whole arch to the left must be resisted by a force and there is then an equal and opposite compressive force on the voussoir. There are two other forces at work, one being the weight of the voussoir, the other being the force from the right-hand point of contact which resists the thrust of the arch up to that point. The voussoir is being held in place, it's in equilibrium, and so these forces must balance each other. You can confirm that forces are in equilibrium if they can form a triangle of forces together.

**Francis Evans:**
Now can anybody guess what will happen if I start putting some weights on this?

**Student:**
It will change the shape of the arch.

**Francis Evans:**
That’s right.  Let’s have a look now and see what happens.  Five hundred grams and here’s a kilogram.  I don’t know if it will take this, we’ll see.  Yep, it’s taken a kilogram and now you see we’ve got a very different shape to the arch.  It’s gone to a different equilibrium, a different balance, and so has the thrust line.

**Narrator:**
If you apply different loads to the voussoir then the compressive forces, and the directions of the thrust, will change to support the variations in the weight.  As long as the arch stands, the voussoir remains in equilibrium, even with a large load like this.